International Experience with Fast Reactor Operation & Testing

International Conference on Fast Reactors and Related Fuel Cycles

Paris, France, March 4-7, 2013

John I. Sackett, INL
C. Grandy, ANL

3/5/2013

www.inl.gov

Idaho National Laboratory

There is a Long History of Fast Reactor Operation

- The first reactor in the world to produce electricity was a fast reactor, the Experimental Breeder Reactor I in December of 1951.
- International experience with fast reactor technology exists in the US, Russia, France, Japan, UK, Germany and India.
- The operating experience with these reactors has been mixed: early problems were associated with fuel cladding, steam generators, fuel handling, and sodium leakage.
- Excellent experience has been gained, however, that demonstrates the robust nature of the technology, the potential for exceedingly safe designs, ease of maintenance, ease of operation and the ability to effectively manage waste from spent fuel.
- It is a mature technology.

EBR-II was a Major Contributor to the Technology

- EBR-I was followed by EBR-II, which was a complete power plant. It was extremely successful, operating for 30 years and advancing the technology in many ways.
- Principal among its contributions were development of metal and oxide fast-reactor fuel, operational-safety tests which demonstrated the self-protecting nature of fast reactors, and fuel-recycle technology that was efficient and secure.
- Perhaps the most important advance in safety was the demonstration of the self -protecting response of sodium-cooled fast reactors in the event of Anticipated Transients without Scram.
- Tests of Loss of Flow without Scram and Loss-of –Heat-Sink without Scram were conducted at EBR-II from full power with no resulting damage to fuel or systems, ushering in worldwide interest in passively safe reactor design.

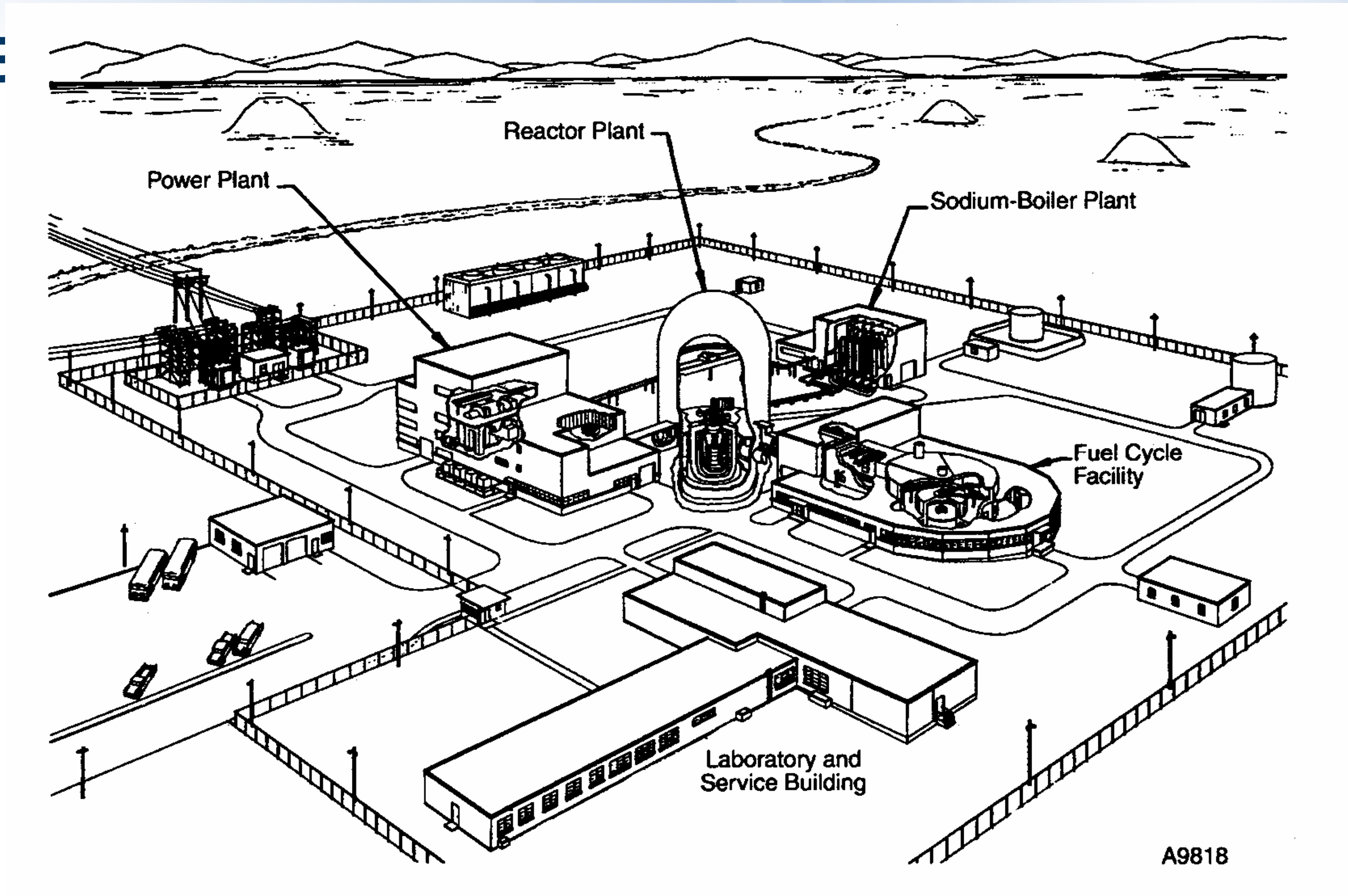
International Experience Compliments These Examples

- This experience base is fully supported by a combination of small test reactors that explored all aspects of the technology and larger operating reactors that provided power to the electric grid.
- Small experimental reactors were operated in the US (EBR-II), France (Rapsodie), Russia (BOR-60), Japan (JOYO), UK (DFR), Germany (KNK-II), and India (FBTR).
- Power reactors and larger experimental reactors were operated in the US (FERMI1, FFTF), France (Phenix, Superphenix), Russia (BN350, BN600), Japan (Monju). Current operating Fast Reactors are China (CEFR), and Russia (BN600, BOR60)

US Experience Followed Two Paths

- The US carried forward two separate tracks of technology development, primarily associated with the choice of fuel, metal or oxide.
- The first US commercial fast reactor, Fermi-I utilized metal fuel while the Fast-Flux-Test-Facility (FFTF) and the Clinch River Breeder Reactor (CRBR) utilized oxide fuel.
- Due to perceived low burnup potential for metal fuel, (a problem later solved), the U.S. approach turned to oxide fuel in the late 1960s.
- Russia, France, Germany and Japan all follow technology paths that use oxide fuel.
- It is worthwhile expanding this point because diversion of the technology paths has resulted in very different designs and performance, with the result that EBR-II is somewhat unique in this family of reactors.

EE


Reactor Plant
Power Plant
Sodium-Boiler Plant
Fuel Cycle Facility
Laboratory and Service Building
A9818

Dry Reprocessing of EBR-II Fuel was Demonstrated in the 1960s

- Melt Refining was used to recycle fuel for EBR-II from 1964 through 1969
  - More than 700 EBR-II fuel assemblies recycled using melt refining and returned to the reactor in four to six weeks
  - ~34,000 fuel pins successfully reprocessed, including remote fabrication by injection casting
  - Spent fuel was disassembled, chopped, placed into a Zr_2O crucible, and heated to 1400 C
  - Chemically reactive fission products reacted with the crucible to form oxides
  - Uranium and noble metals remained in the metallic state and stayed with the melt to be returned with the re-cast fuel pins
  - The fuel was fabricated remotely by injection casting, the resulting equilibrium fuel composition, called fissium, operated through the life of EBR-II

Metal Fuel Data Base

- Over 150,000 metal fuel pins irradiated during the 30-year life of EBR-II
- Seven full-sized assemblies (1800 pins) of metal fuel irradiated to high burn-up in FFTF without failure
- Metal fuel attained 20% burn-up without failure
- Fuel compositions
  - Uranium-zirconium and uranium-zirconium plutonium over a range of plutonium concentrations, with and without additions of minor actinides
- Peak cladding temperatures to 620ºC
- Maximum in-reactor exposures to 5 years

Safety Testing in EBR-II

- Fuel was extensively tested under off-normal conditions
  - Operation with breached cladding (oxide and metal)
  - Transient overpower (TOP) events (EBR-II TOPs complimented more severe TOPs in TREAT)
- Inherently safe response of EBR-II was demonstrated after 12 years of extensive testing and analysis
  - Loss-of –flow without scram (station blackout)
  - Loss-of-heat-sink without scram
- A level one PRA was completed to quantify safety

Fast Reactor Physics has Matured

- The sensitivity of cores to physical changes in core configurations has been seen in a number of “anomalous” reactivity perturbations.
- At EBR-II there was a problem encountered with “flowering” of the core due to problems of the core restraint design.
- The Phenix reactor encountered anomalous reactivity perturbations in four instances, thought to be due to possible “flowering” of the core followed by a rapid return to the original configuration.
- At the FBTR, anomalous reactivity perturbations were also experienced and thought to be associated with changes in core configuration associated with thermal gradients across the core.
- The lesson learned from these events is that proper design of fuel assemblies and core restraint systems is exceedingly important and all phases of operation must be considered.
- The result has been that no or few problems of like nature were experienced in subsequent reactors.

Sodium Leakage

- All operating fast reactors have experienced sodium leaks.
- One of the most famous occurred at the MONJU reactor in 1995 when approximately 640Kg of sodium leaked from the secondary sodium system with a resulting fire.
- A major sodium leak occurred at EBR-II in 1965 when a frozen sodium plug in sodium piping melted during maintenance, releasing approximately 100Kg of secondary sodium.
- As significant as these events were, no injuries resulted nor have any injuries have resulted from leaks at any other operating fast reactors.
- The low pressure of the coolant limits the rate of leakage and improved understanding of designs increasingly prevent and detect leakage.

Steam Generator Failures

- Sodium-steam interaction due to failure of steam generator tubing has also occurred, the most serious at the BN-350 reactor in its early operation. All reactors have experienced steam-sodium leakage with the exception of Superphenix and FBTR.
- In all cases, the failures were traced to poor welds, fabrication or design.
- Much has been learned about prevention, detection and mitigation of the consequences of steam-sodium leakage but perhaps the most important is that such leaks are not catastrophic.
- As with other sodium leaks, no injuries have resulted from failure of steam generators. In addition, physical damage to the plants has been minor.

Reactor Operation is Straightforward

- At EBR-II the reactor was operated with many different core configurations. In all configurations, the reactor was stable in its operation.
- Another aspect is that operating procedures are straightforward, aided by the self-protecting nature of the reactors.
- At EBR-II, extensive tests were conducted that not only included ATWS events associated with loss of flow, but also
  - single rod run-out,
  - primary pump control malfunctions,
  - load following and
  - steam system failures
- These tests also demonstrated that EBR-II was tolerant of operators taking an improper control action.
- These characteristics greatly reduced pressure on operators in the event of off-normal events. Rapid operator response was not required.

Fuel Handling Operations are Challenging

- Fuel handling in sodium-coolant is challenging because there is no visual reference for the operations being conducted.
- Perhaps no fast reactor has had more fuel handling operations than EBR-II, >100,000 operations conducted successfully, but three errors occurred, any one of which could have terminated EBR-II operations.
- Similar events have occurred at other fast reactors. The JOYO reactor suffered significant damage when an experimental assembly was not successfully detached from the fuel handling equipment.
- There have been significant efforts to develop under-sodium viewing technology, which certainly has promise.
- In addition, recent advances in visualization technology such as found in aviation (synthetic vision based upon known location and detailed mapping of terrain) has promise.
- The bottom line is that fuel handling systems deserve extraordinary attention in design, maintenance and operation.

Maintenance is Straightforward

- Maintenance of sodium systems has been shown to be straightforward.
- Sodium systems operate at low pressure which significantly reduces the hazards of leakage during maintenance.
- Since sodium is a solid when cooled below 98^{o} C, it is possible to conduct maintenance on sodium systems without draining them. The typical process is to freeze the sodium where the valve is located, cut the valve out of the system and replace it.
- There are also many examples of successful removal, cleaning and repair of primary-sodium system components such as pumps. At EBR-II, each of the two primary pumps was removed twice.
- At EBR-II, it was found that radiation exposure of maintenance personnel was very low, even though there were many maintenance procedures performed on sodium systems and components.
- Access to the reactor building was not restricted during reactor operation because radiation levels were always very low.

Safety Has Been Demonstrated

- The safety record of fast reactors is outstanding.
- Fast reactors benefit from several operating characteristics that enhance safety.
  - They operate at near atmospheric pressure.
  - The cores are relatively insensitive to spacial power shifts and fission product buildup.
  - Sodium is a very effective heat transfer medium, permitting high core power-densities while effectively removing at decay heat.
  - Sodium is also non-corrosive to fuel cladding and structural components of the core.
  - Passive safety characteristics are easily achieved.
- The technology is robust.

Decommissioning has been demonstrated

- Decommissioning of several sodium-cooled fast reactors has been successfully accomplished.
- The EBR-II reactor was successfully decommissioned after 30 years of operation and both the process and the technology were shown to be effective.
  - There was no evidence of corrosion from the sodium coolant following 40 years containing sodium at high temperature.
- Perhaps one of the most impressive decommissioning efforts was that at BN-350 which went through a similar process with the exception that the sodium was highly contaminated with fission products (principally Cs137) following years of operation with fuel with breached cladding.
- As with any reactor system, a key to successful decommissioning is to anticipate the need in the original design. For fast reactors, it is important that provisions for completely draining the sodium be provided, ensuring that there is no opportunity for residual “pools” of sodium be trapped in spaces that will not drain.

U.S. and International Experience in Fast Reactor Operation Has Shown Many Successes

- Fast reactor fuel is reliable and safe, whether metal or oxide. Cladding failure does not lead to progressive fuel failure.
- High burnup of fast reactor fuel is achievable, whether metal or oxide.
- Sodium is not corrosive to stainless steel or components within it.
- Leakage in steam generating systems with resultant sodium-water reactions does not lead to serious safety problems. Such reactions are not catastrophic, as previously believed, and can be detected, contained and isolated.
- Leakage of high-temperature sodium coolant, leading to a sodium fire, is not catastrophic and can be contained, suppressed and extinguished. There have been no injuries form sodium leakage and fire.
- Fast reactors can be self-protecting against Anticipated Transients Without Scram.

Lessons From Fast Reactor Operation (contd.)

- Passive transition to natural convective core-cooling and passive rejection of decay heat has been demonstrated.
- Reliable control and safety-system response has been demonstrated.
- Low radiation exposures are the norm for operating and plant maintenance personnel.
- Emissions are quite low from sodium cooled fast reactors, in part because sodium reacts chemically with many fission products if fuel cladding is breached.
- Maintenance and repair techniques are well developed and straightforward.

Lessons From Fast Reactor Operation (contd.)

- Several aspects of design and operation have highlighted challenges in fast reactor designs
  - Thermal shock to structures is a major design challenge.
  - Many problems with handling fuel in sodium systems have occurred.
  - Failure of in-sodium components without adequate means for removal and repair has resulted in costly and time-consuming repair.
  - Reactivity anomalies have occurred in a number of fast reactors, requiring careful attention to core restraint system design.
  - Operational problems have been encountered at the sodium/cover-gas interface, resulting from formation of sodium-oxide deposits and can lead to binding of rotating machinery, control-rod drives and contamination of the sodium coolant

Conclusion

- Worldwide experience with fast reactors has demonstrated the robustness of the technology and it stands ready for worldwide deployment.
- The lessons learned are many and there is danger that what has been learned will be forgotten given that there is little activity in fast reactor development at the present time.
- For this reason it is essential that knowledge of fast reactor technology be preserved, an activity supported in the U.S. as well as other countries.